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Diverse and uneven pathways towards transition to low carbon development: The case of diffusion of solar PV technology in China

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Diverse and uneven pathways towards transition to low carbon development: The case of diffusion of solar PV technology in China

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Diverse and uneven pathways towards transition to low carbon development: The case of diffusion of solar PV technology in China

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Abstract

Transition towards low carbon development (LCD) is an urgent challenge for the global community. As increased economic activities usually result in more carbon emissions, this challenge is particularly crucial for rapidly growing emerging countries. For these countries, reducing carbon emissions means taking one or more of the following actions: (1) reducing energy intensity; (2) increasing the use of renewable energy; and (3) introducing systemic change. The above actions call for a strong role of policy and government intervention, as observed in the existing literature based on experiences in developed countries. Emerging countries also need to follow the example of advanced countries with regard to LCD; however, the conditions and pathways for emerging countries may differ greatly. This paper reviews the literature that deals with sustainable transition from a systemic perspective to understand existing frameworks and to identify challenges in using them for observing the transition process in developing countries. It looks at the case of Chinese solar PV technology to link theoretical discussion with practice in order to substantiate the arguments.

JEL CODE: Q42, Q55, Q56
KEYWORDS: Sustainable transition, Low carbon development, Renewable energy, Environmental leapfrogging, Solar PV, Developing and Emerging countries, China

1. Introduction

Transition towards low carbon development (LCD) is an urgent challenge for the global community. As growing economic activities are generally accompanied by increased carbon emissions, this challenge is particularly crucial for rapidly growing emerging countries. For these countries, reducing carbon emissions means taking one or more of the following actions: (1) reducing energy intensity (by reducing the rate of growth); (2) increasing the use of renewable energy; and (3) introducing systemic change. This means that these countries may need to take distinctive pathways towards transition to a more sustainable system.

Transition to a sustainable or lower carbon system calls for a strong role of policy and government intervention. There are frameworks (such as the multi-level perspective, socio-technical transition, transition management, strategic niche management, functions of an innovation system) by which to study the sustainable transition process and come up with effective policy interventions building on research into existing case studies to formulate effective policy. However, the frameworks are created using cases in developed countries, and do not take account of the transition process in developing countries, where there are different challenges. The differences are particularly marked as follows: technological capabilities, absorptive capacity, competing developmental interests, provision of institutions (regulative, normative and cognitive) and role of policy. In order to understand the sustainable transition process and to formulate a better policy for developing countries, the existing frameworks need some adjustment. This paper aims to identify the characteristics of sustainable transition towards a low carbon society in emerging countries by reviewing the existing literature and examining the case of solar PV technology in China.

This paper tries to identify the features of a sustainable transition process in developing countries in order to improve existing frameworks. In the sections to follow, the paper will review these, based on cases from developed countries. This is followed by a review of the literature on sustainable transition in emerging and developing countries. The section will conclude by outlining the transition process in developing countries and suggesting possible areas for improvement in the existing framework. The paper then presents a case of transition in solar PV energy in China to illustrate the uneven and diverse pathways of sustainable transition. The paper will conclude with suggestions for themes for further research in sustainable transition frameworks for developing countries to improve and enhance their policy formulation process.

2. Theoretical discussions

(1) Existing framework to analyse sustainable transitions

A growing amount of research has been conducted to understand the sustainable transition process (Markard et al., 2012; Smith et al., 2010; Jacobsson and Bergek, 2011, among many others). Against a background of increasing research lies a growing concern for environmental sustainability at the global level. The sustainable transition process is not just an introduction of new energy, materials and resource-efficient technology, but involves a much broader change in the system surrounding the technology. It is also a typical case where failures in the market (Arrow, 1962), in the system (Klein Woolthuis et al., 2005), and in the transition process (Weber and Rohracher, 2012)[1] occur

[1] Weber and Rohracher (2012) list several failures: market failure, system failure and transition failure. System failure includes infrastructural, institutional, interaction (network) and capability failure (Klein Woolhuis et al., 2005). Transitional failure includes: (1) directionality failure (direction is determined by the negotiation, policy organization and external costs of a more political nature); (2) demand articulation failure (environmental issues are one of these; underinvestment in market for knowledge, a user-led approach; often public procurement is the answer); (3) policy coordination failure (interaction of different levels), policy mix mismatch/sequence; (4) reflexivity failure: address ability of system of monitoring (Weber and Rohracher, 2012: 1045).

and justify policy intervention. However, without thorough understanding of its evolutionary and structural nature, successful policy formulation for leading the transition will be a difficult task. To this end, several conceptual frameworks have been developed to understand the process of transition and to help formulate effective policy, based on empirical case studies in Europe. These include transition management (Loorback, 2010; Rotmans et al., 2001; Kemp et al., 1998), strategic niche management (Kemp et al., 1998; Smith, 2007; Raven and Geels, 2010), a multi-level perspective on sociotechnical transitions (Geels, 2002; Geels and Schot, 2007; Smith et al., 2010), and functions of innovation systems (Bergek et al., 2008; Hekkert et al., 2007) that use the concept of technological innovation systems (Carlsson and Stankiewicz, 1991).

Existing frameworks are complementary to each other regarding their strengths and weaknesses (Coenen et al., 2010; Farla et al., 2012; Weber and Rohracher, 2012; Coenen et al., 2012). These frameworks can be used in a more integrated manner (Makard and Truffers, 2008) because they share the theoretical origin of systems of innovation and evolutionary economics. The frameworks that are associated more strongly with innovation systems (such as the Technological Innovation System (TIS) and the Sectoral Innovation System (SIS)) generally demonstrate strength in understanding the interactions and inner workings of the actors within the system to analyse and facilitate the development and diffusion of novel technologies (Farla et al., 2012). The key actor in the system is generally the 'firm' for the SIS, due to its clear sectoral boundary, while it is rather unclear and loose for the TIS due to its technological boundary. The TIS, however, is later used in functions of innovation systems to understand how systems emerge and function (Bergek et al., 2008; Hekkert et al., 2007). Functions of innovation systems identify seven key functions: search guidance, entrepreneurial experimentation, knowledge development/diffusion, influence on the direction of search, resource mobilization, market formation, legitimation and development of positive external economies (Bergek et al., 2008) that are essential for building a well-functioning system for creation and diffusion of sustainable technology. This framework also focuses on coordination of sequence and synergy among functions (policy mix), trying to identify inducing and inhibiting factors. In other words, by introducing 'functions' – the outcome of interaction of several actors within the system – the necessary policy interventions to remove the blocking mechanisms are identified more easily.

While the systems of innovation approach is more concerned with the interactions among actors within the system in order to understand its performance (facilitation of innovation via knowledge creation and diffusion) and to formulate effective policy to improve that performance, transition literature (or the multi-level perspective: MLP) is more concerned with the evolutionary process of system transformation by tracing how a certain technology came to dominate – forming a regime configuration – through interaction over time by observing the transformation process at multiple levels: the sociotechnical landscape, sociotechnical regime and technological niches (Geels, 2002; Geels and Schot, 2007; Rip and Kemp, 1998). The sociotechnical regime stems from the concept of the technological regime[2] (Nelson and Winter, 1982), but it includes a broader set of actors that contribute to regime configuration in order to stabilize a certain trajectory of technology. A technological niche is the micro-level radical innovation or 'incubation room' that emerges to 'unlock' the regime configuration (Smith et al., 2010), while the social landscape is an exogenous environment beyond the direct influence of niche and regime actors, such as macroeconomic

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[2] A technological regime (Nelson and Winter, 1977) originally referred primarily to the beliefs and prevailing successful designs that predispose innovators in firms to development of certain apparently marketable or feasible options but away from other less attractive options. This notion was described by Dosi (1982) as technological trajectories and technological paradigms. These are considered to determine the continuity of technology of choice and outlook.

conditions, deep cultural patterns and macro political developments whose speed of change is usually slow (Geels, 2002). Geels (2004: 34) defined landscape as 'a set of heterogeneous, slow changing factors such as cultural and normative values, broad political coalitions, long term economic developments, accumulating environmental programs, growth, emigration'. Although landscape is beyond the control of niche and regime, it is considered to indirectly affect the emergence of a niche and/or destabilize the dominant regime configuration.

It is generally argued that transitions commence when a prevailing sociotechnical regime starts to display significant problems; a key innovation occurs that will become a dominant design; a first and/or early adoption of the transition technology takes place. Research applying the multi-level perspective (MLP) framework to study system transition observed a so-called 'bottom-up' transition process whereby radical change moved from niche to regime level (Smith et al., 2005; Smith et al., 2010; Geels and Deuten, 2006). Building on findings based on historical evidence by system transition studies, transition management studies (Kern and Smith,2008; Hoogma et al., 2002; Kemp et al., 1998, 2001; Schot et al., 1994) emerged with a more interventionist approach that tries to steer the transition process using a long-term future vision (Smith et al., 2005). 'Strategic niche management', on the other hand, places more emphasis on purposively steered policy intervention in small niches to initiate change and manage system transformation strategically in the regime, as against putting too much emphasis on a planned, well-ordered and consensual management process (Smith, 2005; Kemp et al., 2001). Here, the driver of change is at the niche and regime level. The change is initiated either by itself, as the result of interaction with other competing niches, or in reaction with the regime (Geels and Schot, 2010). In this context, landscape remains the context by which to explain the outcome of interaction between niche and regime.

While many advances were made in understanding the transition process using the MLP framework, this approach was criticized for weak conceptualization of agency and for not paying enough attention to conflicting interests and politics in the transition process (Farla et al., 2012). The studies on transition also have a tendency to assume that the causes of change lie within the 'local' heuristic boundary and not so much at the 'global' or landscape level, where everything else external to the 'regime' and 'niche' is bundled together without spatial (such as global, local) considerations (Coenen et al., 2012). For instance, under the current framework of a conceptual 'global' and 'local' distinction, it is not possible to incorporate the influence of the US market as well as competition from the US producers on wind-energy technology development in Denmark. In fact, several empirical studies on solar PV technology have indicated that countries with more exports of renewable energy products (i.e. solar PV) are more likely to have improved capacity to generate power from such technology (Algieri et al., 2011; Sawhney and Khan, 2012). As can be seen, a spatially 'global' stimulus for technological development is not well recognized in the conventional sustainable transition literature, making it difficult to understand irregularities of knowledge flow and development due to uneven access and level of institutional development – such as physical infrastructure, cognitive routines and formal rules (Scott, 1995). The degree of difference in the level of institutional development as well as exposure to interaction with external actors may not be great among developed countries; however, these create substantial differences in developing countries.

(2) Existing studies on sustainable transition in developing countries
a. Environmental leapfrogging
Many works concerning sustainable transition in developing countries originate from discussion on

environmental leapfrogging,[3] whereby latecomer countries can skip the 'dirty' stages by adapting already-available 'cleaner' technology through technological transfer (e.g. Goldenberg, 1988; Unruh, 2000). This view, that developing countries can passively acquire technology through external interaction (such as development assistance, trade and foreign direct investment), proved to be erroneous in later studies, which revealed that 'leap frog' is rather 'hard slog' (Rock et al., 2009) requiring conscious technological efforts to build local capacities in distinctive areas, such as a sufficient level of technological capability and knowledge, stimulating institutional settings, physical infrastructure, conducive social, economic and cultural environment for new technology, and access to the international technology market before being able to adopt/absorb better-performing technology (Perkins, 2003; Gallagher, 2006; Sauter and Watson, 2008; Watson and Sauter, 2011).

For instance, Gallagher (2006: 303) states that leapfrogging is possible only when the country is equipped with technological capabilities to produce or integrate advanced technology, based on the case of the Chinese automobile industry. In other words, the ability to 'transit' to a sustainable or low carbon society depends on the availability of a much broader capacity to absorb knowledge, or 'ability to recognize the value of new information, assimilate it and apply it to commercial ends' (Cohen and Levinthal, 1990: 128), which is very dependent on earlier knowledge/experience – 'path dependence' – and level of technological capability (Bell and Pavitt, 1993), which includes knowledge, skills and experiences, institutional structure and linkage within, between and outside firms to manage technological transition. Put differently, the sustainable transition process cannot be fully understood if the technology alone is studied without paying attention to the role and interaction among local institutions and surrounding actors (Murphy, 2001).

The above view is differently expressed by various studies on environmental leapfrogging. Murphy (2001), after studying the adaption of renewable technologies in African villages, identifies the limitation of focusing only on technology because: (1) technological change is not simply a function of economic supply and demand, but is tied to the social, cultural and political institutions shaping rural communities and households; (2) technological change does not occur in isolation; it happens in sync or in sequence with economic development and social change; (3) the technology alone does not improve the local economies or reduce environmental degradation; people do (2001: 189–90). Gallagher (2006) considers that inconsistent state policies, weak domestic technological capabilities and unwillingness of MNCs to transfer better/cleaner technologies to developing countries (or lack of incentives and regulatory measures to make MNCs do so) are the major inhibiting factors for successful transition. Others mentioned the following as important elements for successful leapfrogging: human and organizational frameworks (Sharif, 1989), policy (Perkins, 2003), local knowledge by all stakeholders (Murphy, 2001; Forsyth, 2005) and organizational structures (Steinmueller, 2001). These indicate that leapfrogging is not just the replacement of a less sustainable technology by a better one, but much more than that. The 'skipping' of technology requires conscious technological efforts very similar to the learning process by reverse engineering of adaptation, imitation and innovation (Kim, 1998). In other words, leapfrogging is a complex, incremental dynamic and systemic process that involves various actors in networks and innovation systems.

How does this process in developing countries differ from that in developed ones? Trukker (2004)

[3]Environmental leapfrogging originates from technological leapfrogging. Soete (1985: 416) defines technological leapfrogging thus: 'Far from developing factor proportions, appropriate industries and technologies both for the domestic and export world market, the opportunities offered by the international diffusion of technology to jump particular technological paradigms and import the more, if not most, sophisticated technologies that will neither displace the capital invested nor the skilled labour of the previous technological paradigm, constitute one of the most crucial advantages of newly industrialization countries in their bid for rapid industrialization.'

tried to identify the different patterns of environmental leapfrogging among developed ('matured'), emerging and developing ('surviving') countries. He found that there are differences in barriers to change by level of development. This was particularly true for the sector that requires large infrastructure such as energy. He considered that developing countries suffer fewer barriers to adapting new technologies because these countries suffer less from path dependence due to lack or underdevelopment of systems. His analysis leads us to believe that, in many ways, the sustainable transition process varies a great deal by level of development.

The above observations lead us to the importance of using an innovation systems (IS) framework to analyse sustainable transition. The existing frameworks that combine the IS and the MLP framework enable us to observe the complex and evolutionary changes accompanied by new technology, paying attention to local technological capabilities, institutional provisions and cultural, social and economic conditions that are conducive to supporting the transition process, as discussed in the previous section. The important question is whether the existing framework can accommodate the peculiarity of developing countries as sketched by Trukker (2004). The next section will review some case studies on sustainable transition in developing countries to explore this point.

b. Sustainable transition in developing countries: cases from emerging Asia and developing Africa

A limited number of studies has been conducted on the sustainable transition process in developing countries using the framework mentioned in the previous section (Tigabu et al., 2013; Bai et al., 2009; Angel and Rock, 2009; Berkhout et al., 2009a; Berkhout et al., 2009b; Rock et al., 2009; Binz et al., 2012; van Alphen et al., 2008). Among others, case studies in Asia clearly illustrated the peculiarities of catching-up countries in the sustainable transition process. These are: strong influence of a global impact in stimulating agents' behaviour; strong role of state/policy intervention such as overarching export-led liberal economic strategy; and level of local capability in shaping the configuration of a sociotechnical regime. Some of the above points coincide with the shortcomings identified by Farla et al. (2012) with regard to the role of agent and Coenen et al. (2012) with regard to lack of a global aspect of the framework in a spatial sense.

Several studies (Berkhout et al., 2009a, 2009b; Rock et al., 2009; Bai et al., 2009; Angel and Rock, 2009) paid particular attention to the impact of globalization in sustainable transition. Among these studies, Rock et al. (2009) changed the concept of the landscape in a multi-level perspective (MLP) framework into a sociopolitical landscape in order to incorporate the role of overarching industrial strategy in emerging Asian export-oriented countries. The sociopolitical landscape includes features such as the government's long-run vision, the local competitive environment among firms, an open trade policy, investment and technology that influence the configuration of a regime as firms interact with external influences (trade, FDI, migration of skilled labour). Rock et al. (2009) identified the influence of the sociopolitical landscape and the interaction with global actors in the sustainable transition process using the cases of Siam cement in Thailand and Motorola in Malaysia. In the case of Siam cement, the destination market's product specification influenced the agent to use more sustainable technology, while Motorola had a global strategy of using sustainable technology in subsidiaries. In both cases, these firms had to upgrade their sustainable trajectories due to global linkages (through either export or FDI). Similarly, Angel and Rock (2009) found that firms with global linkages in East Asian newly industrializing countries (NICs) are sensitive to global market conditions (such as the emergence of end-market environmental regulations) and these can be a driver of environmental transition. At the same time, these countries are active in obtaining technology by making conscious efforts such as global searching for technological options and opportunities, international sourcing via purchase of capital goods, and building international science and technology networks by consulting experts. Furthermore, as a result of these global interactions, political elites became conscious of the global agenda, such as sustainability to translate into the local political dialogue. Openness in many East Asian NICs thus shapes the dynamic interplay of niches, regimes and landscapes to influence the transition process at the sociopolitical level. It should be emphasized that the above evidence demonstrates that landscape—spatially global level—has a great deal of influence in shaping regime configurations in emerging Asia, unlike the conventional sustainable transition in developed countries.

Binz et al. (2012) studied the case of Chinese wastewater management technology to analyse leapfrogging potential using a transition framework that pays attention to spatial dimensions. The case demonstrated the emergence of domestic TIS in China and its integration process into international TIS. This study identified the presence of a spatial aspect of knowledge flow that takes place in an uneven manner at local and global levels due to fragmented distribution of access and capability to absorb the new technology. For instance, Binz et al. (2012) stated that wider acceptance of technology would require time, capability and strong political will because rural people, especially the poorest, cannot rapidly accept new technology due to limited access and capability. This means that successful sustainable transition – or environmental leapfrogging – may require a long gestation period of continuous technological efforts along with global exposure in accessing knowledge.

Other case studies undertaken to examine the diffusion of renewable energy technologies in developing countries, applying the function of innovation systems framework, exist for the Maldives (van Alphen et al., 2008) and Kenya and Rwanda (Tigabu et al., 2013). The cases of the Maldives and Kenya were not successful in regard to diffusion despite many efforts aimed at knowledge diffusion and training by various international agencies and NGOs. In contrast, the more successful case of Rwanda demonstrates the importance of local initiatives by the agent in the form of clear policy and conscious technological efforts. This evidence clearly emphasizes the important combination of the role played by the agent; conscious technological efforts in the form of policy; and exposure to external knowledge and local capability for sustainable transition to occur. These findings are in line with earlier arguments on environmental leapfrogging and a sustainable transition framework.

3. Research questions

Transition to a more sustainable, low carbon society is a hard global challenge today. With increasing economic activities, carbon emissions are expected to increase in emerging and developing countries. Leading the countries towards a lower carbon pathway is an increasingly important yet difficult task. A number of environmental transition studies have contributed in creating useful frameworks based on the innovation systems and evolutionary economics approach to observe and guide/manage the transition process. Such an approach is very useful for emerging and developing countries because successful sustainable technological diffusion and adaption – environmental leapfrogging – implies a cumulative, systemic and evolutionary process involving various actors in a network and the frameworks to facilitate coordination. Despite this growing importance, limited studies exist that observe the transition process in developing and emerging countries, while existing studies have demonstrated the shortcomings of these frameworks, which are based on European cases, in meeting the real challenges of developing countries. The question addressed in this paper is: What characteristics are observed in emerging and developing countries in the sustainable transition process? The identification of these characteristics is deemed important to improving existing frameworks.

The review of literature in both developed and developing countries has identified the following as possibly important factors in determining the success of sustainable transition, particularly in emerging and developing countries: access to global knowledge through interaction at the landscape level; presence of coherent policy, with an agent to determine the underlying condition for regime configuration; and conscious efforts made to build technological capability, absorptive capacity and institutions. Clear understanding of these characteristics based on a case study would help to improve existing frameworks and the policy formulation process. The following section attempts to demonstrate the transition process of solar PV technology in China. The case study aims to put the findings from previous studies in a dynamic context in a fast-growing country.

4. The case of solar PV energy technology in China

(1) China and solar PV energy

China has experienced exceptional economic growth and export performance since the 1990s. Rapid growth in energy consumption has increased carbon emissions, making China an important player in climate-change negotiations. China has designed various policies to mitigate carbon emissions in the following main way: increase the industrial base of clean technology manufacturing as well as renewable energy generation capacity. As the result of these efforts, China (as of 2012) has the largest capacity for renewable power generation in the world, followed by the USA and Germany, and is one of the five largest countries in the world in terms of capacity for producing the following types of renewable energy: bio-power (3rd), hydropower (1st), solar PV (4th), wind power (1st), solar water collection (1st), geothermal (2nd) in 2012 (REN21, 2013). As for manufacturing capacity, several Chinese firms, such as Goldwind, Sinovel and Migyang for wind energy and Yingli Green Energy and Trina Solar – to name a few – for solar PV, are considered the dominant players in the global export market for both wind turbine and solar PV respectively. The growing presence of China in terms of capacity to generate and manufacture renewable energy is accompanied by a growing capacity to innovate as the result of conscious efforts made by both private and public sectors. In this section, different types of capacity development efforts – to generate, to manufacture and to innovate – towards renewable energy are examined to understand the characteristics of China's sustainable transition process, as well as how these capacities have interacted to shape the sustainable transition by focusing on solar PV. Despite the impressive growth in generating capacity in recent years, China's solar PV was not a substantial source among forms of renewable energy until recently. We will examine how this transition towards more generating capacity of PV – a transition to a more sustainable energy source – came about, paying attention to the points identified in the literature survey. These are: presence of technological capability and absorptive capacity; exposure to the external market through exports and domestic policy; and developmental strategies to support the transition process.

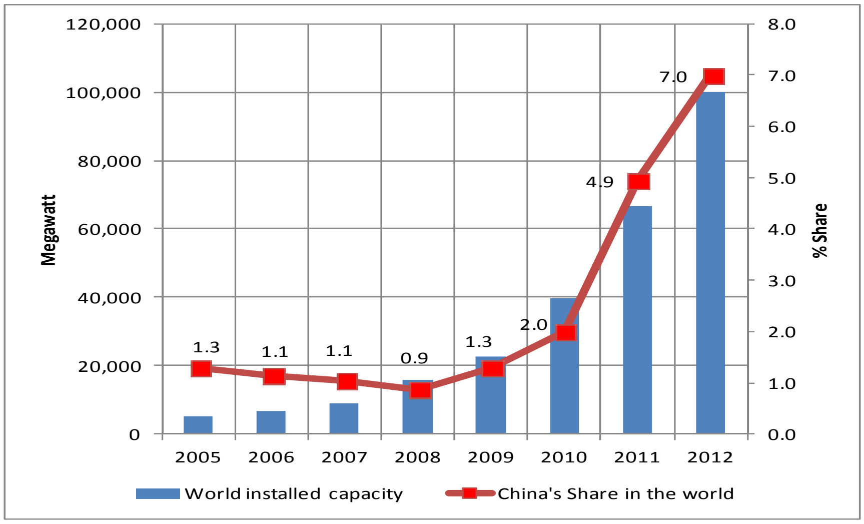
(2) Generating capacity of solar PV: rapid growth in China since 2010

The growth of solar PV systems is a relatively recent trend at the global level. Until the late 1990s, PV systems were installed almost exclusively off the grid for electrification of remote and rural areas, telecommunications, meteorology, transportation, light chargers and other commercial products and industries. From 1996 to 2003 the world's on-grid solar capacity grew rapidly from 0.7 GW to 2.8 GW. After 2005, there was accelerated growth in energy capacity, from 5.4 GW in 2005 to 100 GW in 2012. Germany currently leads with its share of the world's solar PV generating capacity, with 32 per cent, followed by Italy with 16 per cent and the USA with 7.2 per cent. Our case study, China, is in fourth place in the world for generating capacity in 2012 (REN21, 2013).

For a long time the use of solar PV in China was not extensive, limited to the off-grid system to electrify remote and rural areas. On-grid solar PV energy generating capacity grew very slowly until 2010 and then increased dramatically. For instance, the share of installed capacity of solar PV in China increased to almost 7 per cent of world solar energy capacity in 2012 from 0.07 per cent in

2005 (REN21, 2011; Zhang and He, 2013; REN21, 2013) (Figure 1). The increase over the years can be considered as the result of various policies introduced to encourage deployment of solar PV technology.

Figure 1 Cumulative installed capacity of solar PV in the world and in China (unit: megawatts, MW)



Source: Based on REN21 (2013) and Zhang and He (2013).

(3) Manufacturing solar PV: China leads in export and intensifies price competition

In 2011, the aggregate size of the global PV industry is said to have exceeded US$100 billion. Over the past decade, the nationality of leading manufacturers has changed, from the USA to Japan, then to Europe and now to other Asian countries, especially to China. In 2008, China accounted for 35 per cent of the worldwide production of PV cells. In 2010, firms from China and Taiwan accounted for 59 per cent of global PV module production, up from 50 per cent in 2009. In 2012, 9 of the 15 largest PV cell production companies globally were Chinese (see Table 1), most of which were vertically integrated along the core part of the production value chain (i.e. they produce wafers, ingots, cells and modules). In China, PV module production was originally for domestic use in rural areas, but from around the 2000s, especially after 2006, exports increased sharply owing to the growth of the large subsidy market in the EU – with demand generating policies such as feed-in tariffs, renewable energy portfolios and tax measures. It is said that, in 2009, 95 per cent of the national production was exported (de la Tour et al.., 2011); however, as seen from solar PV energy generating capacity, domestic use was not part of this until recently. In fact, unlike other renewable energy sectors such as hydropower, bio-power and wind, solar PV power generation's domestic market was underdeveloped until 2010 in China.

As far as the manufacturing of solar PV is concerned, the rapidly changing league table of firms indicates the harsh competition in this sector. Such rapid change in price competition is led mainly by China. The low-cost solar modules produced by China are making it difficult for incumbent solar panel producers to compete, even with government subsidies, in respective countries. In fact, between 2011 and 2012, large players such as Solyndra (USA), Q-Cells (Germany), BP Solar and many others pulled out of the solar PV industry. Some have diminished their scale of operation, such as Sharp (Japan) and First Solar (USA) (REN21, 2012). In 2013 price competition even affected one of the leading Chinese manufacturers, Suntech.[4] Price competition also triggered trade disputes

[4] Suntech, the leading Chinese solar PV manufacturer, went bankrupt and was acquired by the Chinese government in March

between China and its major destination market, the EU. as well as the USA. This trade dispute, and its settlement in August 2013, also created a difficult situation for other Chinese manufacturers. To mitigate overheated competition, the Chinese government announced a limit on the number of firms in the solar PV business to the top 134 firms (*Nikkei e*, 2013, Feng and Enkhardt, 2013.). This was also targeted to manage the trajectory of Chinese competition, in order to focus more on higher-value-added than low-value-added products.

Table 1 Leading PV module manufacturers by percentage share in the world market

	2010	country	%		2011	country	%		2012	country	%
1	Suntech Power	China	7.0	1	Suntech Power	China	5.8	1	Yingli Green Energy	China	6.7
2	JA Solar	China	6.0	2	First power	USA	5.7	2	First power	USA	5.3
3	First Solar	USA	6.0	3	Yingli Green Energy	China	4.8	3	Trina Solar	China	4.7
4	Yingli Green Energy	China	5.0	4	Trina Solar	China	4.3	3	Suntech Power	China	4.7
4	Trina Solar	China	5.0	5	Canadian Solar	Canada	4.0	5	Canadian Solar	Canada	4.6
6	Q-Cells	Germany	4.0	6	Sharp	Japan	2.8	6	Sharp	Japan	3.0
7	Kyocera	Japan	3.0	6	Sun power	USA	2.8	6	JA Solar	China	2.8
7	Motech	Taiwan	3.0	8	Tianwei New Energy	China	2.7	8	Jinko Solar	China	2.6
7	Sharp	Japan	3.0	8	Hanwha-SolarOne	China	2.7	8	Sunpower	USA	2.6
7	Gintech	Taiwan	3.0	10	LDK Solar	China	2.5	10	Hareon Solar	China	2.5
10	Hanwha-Solar One	China	2.0	10	Hareon Solar	China	2.5	10	Hanwha-SolarOne	China	2.5
10	Neo Solar	China	2.0	12	JA Solar	China	2.4	12	Renesola	China	2.1
10	Canadian Solar	China	2.0	13	Jinko Solar	China	2.3	13	Kyocera	Japan	2.1
10	Sunpower	USA	2.0	14	Kyocera	Japan	1.9	14	REC	Norway	2.0
10	REC	Norway	2.0	14	REC	Norway	1.9	14	Tianwei New Energy	China	2.0
Total share of top 15 firms			**55.0**	**Total share of top 15 firms**			**49.1**	**Total share of top 15 firms**			**50.2**
	of which by China		**29.0**		**of which by China**		**30.0**		**of which by China**		**30.6**

Source: Based on REN21 (2011) and (2013).
Note: Suntech Power went bankrupt in March 2013.

(4) China's technological efforts in solar PV: leapfrogging?

The growing manufacturing capacity demonstrated by China's export performance was accompanied by increasing technological efforts. Both government and firms attempted to close the technological gap with OECD countries. The results of these efforts can be observed from the rapid increase of indigenous R&D. Between 1996 and 2008, central government R&D appropriation for renewable energy increased from RMB 21.1 billion (US$2.5 billion) to RMB104.8 billion (US$15.2 billion), while expenditure by regional governments for the same purpose increased from RMB 7.8 billion (US$940 million) to RMB 105.7 billion (US$15.4billion) (Cao and Groba, 2013). Such an increase in expenditure was backed by government policy, as will be discussed in the following section. Parallel to such technological efforts, Chinese firms relied on the acquisition of foreign technologies using turnkey cell and module production lines and capital goods from the late 1990s to the early 2000s (de la Tour et al., 2011). During this time, the manufacturing activities of Chinese solar PV firms were concentrated on 'easy-to-enter' but 'low-profit-margin' activities of cell and module production (see Table 2).

2013 (*Nikkei*, 2013).

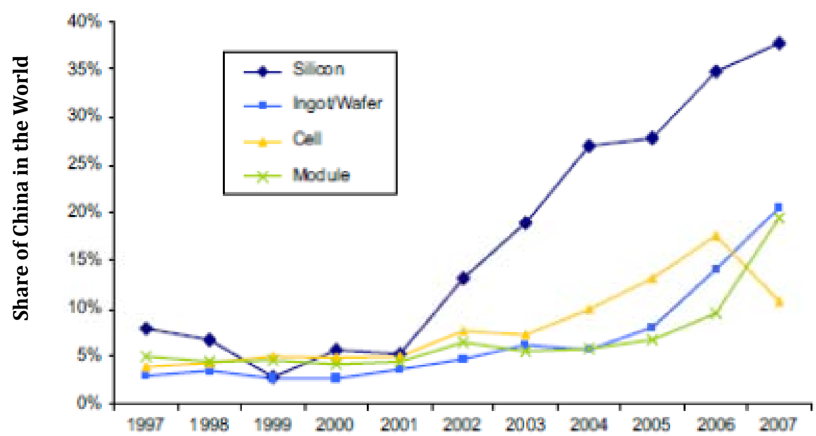
Table 2 Solar PV by technology component in 2007

	Silicon	Ingot/wafer	Cells	Module
Market share by China	2.5%	< 5.0%	27.0%	
Percentage of cost in a panel	13%	27%	27%	33%
Percentage of profit in a panel	41%	41%	11%	7%
Intial investments (millions)	US$140	US$95	US$125	US$25
Level of technological barrier	High	Medium/high	Medium/low	Low

Source: Based on de la Tour et al. (2011).

Subsequently, these firms' cumulative efforts at in-house R&D were complemented by strategies of joint R&D with universities and research institutes, as well as setting up overseas R&D facilities with government inducements for acquiring technology. Such R&D focused on crystalline silicon, which was the dominant technology at that time. Although the strongest presence of Chinese firms is still in downstream activities, i.e. cell and module production, firms have also invested in upstream activities such as the processing of silicon feedstock. By the mid-2000s, efforts to increase national production of silicon had been put in place, but they still do not completely fulfil national demand, and had to be supplemented by imports from abroad (Marigo, 2006).

Figure 2 Share of Chinese patent applications by segment of solar PV



Source: de la Tour et al. (2011).

The outcomes of such R&D efforts can also be seen from the gradual increase in patent applications for the more technologically intensive aspects, e.g. silicon. The overall share of patents is also increasing for silicon[5] (de la Tour et al., 2011) (Figure 2). At a more global level, analysis of first-time patents (i.e. excluding patents subsequently filed in other patenting offices) for selected climate-change mitigation technologies (CCMTs),[6] including solar PV, filed at the European Patent

[5] Of course, interpreting numbers of patent applications requires caution; they cannot always be interpreted as an increase in technological capacity.

[6] Based on the findings of existing studies, the OECD study (Hascic et al., 2010) included the following technologies in climate-change mitigation technologies (CCMTs): solar (photovoltaic, thermal, hybrid), wind (on- and offshore), geothermal, hydro, marine/ocean (kinetic, saline, and thermal), biofuels (biomass heat/power), and fossil/coal (integrated gasification combined cycle: IGCC, CO_2 capture and storage). In our paper, we refer only to solar (photovoltaic) data.

Office (EPO) based on the OECD World Patent Statistics (PATSTAT) database for the period between 1988 and 2007[7] (Hascic et al., 2010) shows that China, among the emerging countries, had the highest share of solar PV patents at 0.9 per cent, followed by India (0.3 per cent) and Russia (0.1 per cent). The share of China in solar PV patents is small compared with the leading patenting countries, such as Japan (44 per cent), the USA (15 per cent), Germany (10 per cent) and South Korea (9 per cent). However, if compared with other developed countries such as Canada with 0.6 per cent and Spain with 0.3 per cent, China's share is not significantly low (Hascic et al., 2010) (see Table 3).

Table 3 Share of patent in solar PV technology (1988–2007)

Share of patent in Solar PV technology (%)		
1	JAPAN	43.9
2	UNITED STATES	14.5
3	GERMANY	10.4
4	KOREA	8.9
5	FRANCE	2.7
6	GREAT BRITAIN	2.4
7	TAIWAN	1.8
8	NETHERLANDS	1.1
9	ITALY	1.0
10	CANADA	0.6
11	SPAIN	0.3
	DENMARK	0.1
	CHINA	0.9
	INDIA	0.3
	RUSSIA	0.1
	BRAZIL	0.0
Rest of countries		11.1
World total		100.0
total no. of patents		8972

Source: Based on Hascic et al. (2010).
Note: In these data, the country of origin of the technology is determined by the country in which the inventor resides.

If we observe the technological flow in solar PV technology by looking at the duplication of patent applications,[8] we can see that China has the highest number of secondary patents filed (2055) among other emerging countries, leading by far in relation to Brazil (96) during 1988–2000 (Table 4). Again, the purpose of patenting activities in emerging countries may vary across countries and firms (Hall and Helmers, 2010); however, it is possible to infer that these numbers reflect the rapid growth of domestic markets and/or production activities for solar PV technology in China.

[7] The cumulative number of patents filed over the period from 1988 to 2007 in aggregate form does not show the yearly differences in patenting activities and is possibly biased towards the early developers of these technologies and against the emerging countries.

[8] In the report by Hascic et al. (2010), duplicate patent applications, in which a patent originally filed in a country for the first time is subsequently filed in different patent offices, are considered as a sign of technological flow. Given the variety in purpose of patenting activities by firms (as summarized in Hall and Helmers, 2010), these figures should be understood as an indication of trends in technological activities in the emerging countries with regard to technology developed in other countries.

Table 4 Number of duplicate patent applications, solar PV technology (1988–2008)

	Receiving country**	CHINA	BRAZIL	SOUTH AFRICA	INDIA	TOTAL OF LISTED
Source of technology*	JAPAN	1067	7	1	1	1076
	UNITED STATES	663	47	11	2	723
	GERMANY	185	19	9	1	214
	GREAT BRITAIN	57	6	8	2	73
	FRANCE	35	8	7		50
	AUSTRALIA	18	3	5		26
	NORWAY	9	2			11
	NETHERLANDS	10	4	1		15
	ITALY	5				5
	SWEDEN	6				6
	TOTAL OF ABOVE	2055	96	42	6	2199

Source: Based on Hascic et al. (2010).
Note: *Source of technology indicates the origin of technology, determined by the country of residence of the inventor, when it was patented for the first time based on the EPO database. **Receiving country is the nationality of the patenting office when the patent was applied for the second time.

Wu and Mathews (2012) compared knowledge flows of solar PV technology in Taiwan, Korea and China, using USPTO patent data from 1984 to 2008. They also found similar results to those of Hascic et al. (2010). Wu and Mathews (2012) discovered that, in China, knowledge flows went from advanced countries such as Japan and the USA for first-generation technology[9] for solar PV; however, for second and third generations, China started to participate more in patenting as well as actively establishing scientific linkages, as seen from citation patterns. This demonstrates the gradual build-up of technological capability in China. Furthermore, the fact that China actively participates in second- and third-generation technology but not in first-generation indicates technological leapfrogging.

(5) China' policy efforts in the diffusion of solar PV technology

Chinese renewable energy policy concerning solar technology dates back to 1996, with the 'Brightness Program' of China's former State Planning Commission. This programme aimed to provide electricity in rural areas not connected to the grid by using PV modules and wind-power systems. The Township Electrification programme, formulated by the National Development and Reform Commission (NDRC) in 2002, followed this programme with a similar aim. This programme constructed solar PV power stations in 688 towns (out of 1065 targeted) to resolve rural electrification needs. In the early days, these government policies stimulated and nurtured the development of China's solar PV industry, but deployment in the domestic market was not as strongly supported as wind technology (Zhang and He, 2013), which was more cost-effective at this time. As shown in Figure 1, the generating capacity of solar PV in China stayed low until 2008.

At the early stage, the development of China's solar PV industry was led mainly by creation of demand in Europe and the USA, caused by the introduction of subsidies and feed-in tariffs.[10] These tariffs triggered waves of large-scale installation in European countries and greatly boosted

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[9] Wu and Mathews (2012) distinguished five decades of solar PV technologies as three generations: first generation (1G) using c-Si in its earlier monocrystalline and polycrystalline forms; second generation (2G, so-called thin-film) utilizing amorphous silicon (A-Si), cadmium telluride (CdTe), copper–indium–gallium selenide (CIGS), and gallium–arsenide; and third generation (3G) using organic compounds (such as sensitized solar cells).

[10] For instance, the German Renewable Energy Act (EEG, Erneuerbare-Energien-Gesetz) strengthened the nation's feed-in tariff, and was soon emulated in other top solar markets such as Spain and Italy (Butler et al., 2008; Commission of the European Communities, 2005, 2008; German Renewable Energy Agency, 2012; Photovoltaique, 2008, quoted in Liu and Goldstein, 2013).

demand for China's solar PV exports, at precisely the time that Chinese producers were expanding output and capacity. Many firms were quickly being established, with returning engineers entering the relatively easier sector of production (de la Tour et al., 2011). During this time, Chinese PV cell and module exporters did not have specific policy support from the state other than generic support for exporting firms (such as State High Tech Development Plan in 1986, Science, Technology Law in 1993 and National Basic Research Program in 1997 see table 5). The support for solar PV manufacturers, however, became prevalent around 2009 when the global recession caused reductions in overall export demands as well as subsidies and feed-in tariffs in the European market, affecting the export performance of Chinese firms.

State support for solar technology policy began around 2009, after Chinese PV cell and module manufacturers had established an important position in the world market. One form of support was to increase Chinese companies' share of the upstream segments (such as silicon) of solar technology by subsidizing R&D (as seen in the previous section). The Chinese government also implemented a policy to save the exporters of PV cells and modules, which were affected by the economic crisis of 2008. These firms are, in general, overinvested in production capacities, and this deteriorated their price structure. Hence the Chinese government, in order to save these firms, initiated a wide range of supports, such as reintroduction of explicit export subsidies to sustain employment and social stability, as well as export performance (Yardley, 2008). It is said that these firms also had subsidized credit from state-owned banks (Bradsher, 2009). These government supports created a significant advantage for Chinese solar PV producers by offsetting higher shipping costs (Goodrich et al., 2011), and therefore Chinese producers outcompeted many manufacturers in the USA and Europe.[11]

As well as subsidizing exporting solar PV manufacturers, the government also started to support domestic deployment from 2009. This included support for both grid-connected solar module installations and distributed solar capacity for off-grid settings (Burgermeister, 2009, quoted in Liu and Goldstein, 2013). For instance, in 2009, the 'Rooftop subsidy program' and the 'Golden Sun Demonstration Program' were introduced, together with reform of the renewable energy law of 2006 (Zhang and He, 2013). The 'Rooftop subsidy program' was formulated by the Ministry of Finance and Ministry of Housing and Urban Rural Development of China in March 2009. This provides subsidies for rooftop systems (upfront RMB 15/W) and for Building Integrated Photovoltaic (BIPV) systems (upfront RMB 20/W), and subsidized 50 per cent of the cost of supplying critical components for on-grid PV systems. The 'Golden Sun Demonstration Program' was formulated by the Ministry of Science and Technology and the National Energy Administration in July 2009. This programme supported large (more than 500 MW) solar PV projects for a 2–3-year period (Zhang and He, 2013). Both programmes have continued to run until now. In addition to the above, two rounds of public tender for solar-powered projects were implemented in 2009. It is said that these government incentives stimulated the solar PV domestic market in China.

In 2011, to encourage this development, the National Feed in Tariff (FIT) scheme was announced by the National Development and Reform Commission (NDRC) (Zhang and He, 2013). In 2012, the National Energy Administration (NEA) issued *The 12th Five Year Plan for Renewable Energy Development*, which demonstrated clearly the plan to invest in renewable energy, including solar energy, especially by establishing the grid system and mobilizing local government consumers and other important actors. As can be seen from Table 5, numerous policies were introduced in 2012 to

[11] In 2012, the US Department of Commerce, in imposing a new set of tariffs, concluded that Chinese solar PV exporters had received subsidies ranging from 2.90 to 4.74 per cent (International Trade Administration, 2012, quoted in Liu and Goldstein, 2013).

stimulate deployment of renewable energy with regard to solar PV in particular.
<Table 5 near here>

In 2012, the share of installed capacity of solar PV in China increased to 7 per cent of world solar capacity, from 1 per cent in 2008 (REN21, 2011; Zhang and He, 2013) (Figure 1). This increase had much to do with the above change in national policy that focuses more on promoting the deployment of solar PV technology in the domestic market as a measure to rescue the domestic solar PV industry amidst trade friction with the EU and the USA in mid-2012 (Liu and Goldstein, 2013).

Table 5 National and provincial government policies and programmes targeting renewable energy and solar PV technology

Year	Policy
1986	State High-Tech Development Plan (863 programs)
1993	Science and Technology Law
1996	Brightness Program
1997	National Basic Research program (973 Programs)
1998	Energy Conservation Law
2001/03	Reduced Value Added Tax for Renewable Energy
2006/2009	Renewable Energy Law
2006	Renewable Energy Electricity Price sharing and Management
2007	Shandon Province Energy Fund
2007	Notice on construction of Large-Scale Solar PV Power Plants
2008	Shandon Province Village Renewable Energy Regulation
2008	Shandon Province One Million Rooftop Sunshine Plan
2008	Tenth Renewable Energy Five-Year Plan
2009	Rooftop Subsidy Program
2009	State Council Notice on Energy Conservation and Emission Reduction
2009	Renewable Energy Law Amendments
2009	Renewable Electricity Surcharge (amended in 2011)
2009	Golden Sun Demonstration Program (revised in 2011)
2010	Building Integrated Solar PV Program
2010	Interim Feed-In Tariff for Four Ningxia Solar Projects
2011	Solar PV National Feed-in Tariff
2011	The Twelfth Five Year Plan for National Economic and Social Development of the Peoples Republic of China
2011 (Dec 15)	The Twelfth Five Year Plan for Renewable Energy of Beijing
2012 (Jan1)	Notice on Vehicle and Vesse Tax Reduction for Energy Saving and New Energy Automobiles
2012(Jan1)	Interim Measures on Renewable Energy Development Fund Imposition and Management
2012 (Feb 24)	Solar Industry Twelfth Five Year Development Plan
2012 (Mar 14)	The Renewable Energy Tariff Surcharge Grant Funds Management Approach
2012 (Mar 27)	Solar Power Technology Development Twelfth Five Year plan
2012 (May 25)	The Notice on New Energy Demonstration City and Industrial Park
2012 (June 12)	Renewable Energy Electricity Feed-In Tariff
2012 (June 28)	Energy Saving and New Energy Automotive Industry Development Plan 2012-2020
2012 (July 9)	Twelfth Five Year Plan for National Strategic Emerging Industries
2012 (Aug 8)	The Twelfth Five Year plan for Renewable Energy
2012 (Sept 14)	The Notice on the Establishment of Demonstration Area for Large Scale Solar PV Power Generation
2012 (Oct 24)	China Energy White Paper 2012
2012 (Oct 26)	Interim Measure of Distributed Solar Power Generation on Grid Service Agreement

Source: Author, based on Cao and Groba (2013); IEA/IRENA joint policies and measures database www.iea.org/policiesandmeasures/renewableneergy/, accessed 10 December; Liu and Goldstein (2013).

Despite the government's many efforts to increase domestic demand from early 2012 to compensate for the decline in the European and the US market due to their respective recessions, the overheated price war due to increased production capacity caused the bankruptcy of Suntech, a leading Chinese solar PV manufacturing firm, in March 2013. The trade disputes with Europe and the USA that started in 2012 also made the situation very difficult. The trade dispute agreement was reached on 27 July and implemented on 6 August 2013, basically with China accepting a minimum price and quota for export to Europe. While dealing with these trade disputes, the Chinese government announced two measures in autumn 2013. One is a 50 per cent discount in value added tax for all exporting firms until the end of 2015 to mitigate the impact of the trade dispute settlement. Another is the introduction of a new guideline for the solar PV industry. This guideline essentially selects what kinds of firms can get financial support from government, but the conditions for such finance show clearly that the government is trying to upgrade the technological competitiveness of the Chinese solar PV industry.[12]

5. Discussion and conclusion

A remarkable increase in energy-generating capacity by solar PV has been achieved in China in recent years. On the surface, this looks like the fruit of implementing effective policy measures. However, it can also be considered as a windfall benefit from global interaction, including fall in demand due to crisis in 2008 and trade disputes with the EU and the USA concerning solar PV modules and components that took place in 2012. These changes in global market had triggered and consolidated the shift in policy to deploy solar PV technology in the domestic market (*Nikkei a, b, c*, 2013; Liu and Goldstein, 2013). Firm strategy has also changed during the period. Several Chinese firms are now looking to expand their market in other emerging and developing markets in Asia, Africa and Latin America (*Nikkei d*, 2013); while at the same time they are required to invest in the high-value-added segment of the production chain by the government guideline introduced in 2013. The exports of cost effective and better equipment by Chinese manufacturers may increase the generation of renewable energy in other developing countries, contributing to the overall transition to low carbon development.

In other words, the external change at the landscape—global—level has affected the export-oriented Chinese solar PV industry significantly, leading to changes in both firms' and the government's policy to target diffusion of use to the domestic market. This will contribute to achieving a sustainable transition. Such a transition, however, is not only caused by the change in policy induced by external change, because this could not have materialized on such a scale without the firm-level technological capability cumulatively acquired through interacting with export markets and support from government by means of numerous policy interventions dating back to the 1980s. As various studies have shown, Chinese solar PV manufacturing acquired technological capability, first through reverse learning via incumbent players such as Japan and the USA (for first-generation technology) (Wu and Mathews, 2012), and by producing low-barrier technological components (de la Tour et al., 2011), then by leapfrogging to second- and third-generation technology by building scientific linkages with Germany (Wu and Mathews, 2012) and starting to patent higher-barrier technologies such as silicone and ingots (de la Tour et al., 2011; Wu and Matthews, 2012). Hence it is possible to say that the sustainable transition – here the increase in solar PV energy-generating capacity in China –happened as the combined result of being open to the external market and agents (both government and firms), reacting reflexively and swiftly to external changes with appropriate strategies and technological capability, and absorptive capacity accumulated through long-term government support and interaction with global players.

[12] This consists of complying with the following minimum requirements: at least 3 per cent of annual revenue to be invested in R&D and/or improvement of technology; prohibit firms from investing only in production capacities; and stricter regulations on production requirements for energy consumption, environmental protection and quality management for solar PV manufacturing firms. There were also strict requirements for firms to produce a certain proportion of ingots, solar cells and thin films to demonstrate the higher technological capacity level (Feng and Enkherdt, 12 September 2013). The guideline was announced in September 2013 and went in force 30 days later.

Unlike wind energy (documented by Lema and Lema, 2012; Waltz and Delgado, 2012; Lewis, 2007), whose development in use, manufacturing and technological capacity was carefully guided by government policy, the driving force for development of solar PV technology was external market demand in Europe and the USA. In this sense, even though both renewable technologies exist in China, each technology has different pathways with regard to how it can contribute to the sustainable transition to low-carbon development. The solar PV industry in China has learned the use of technology in reverse order by acquiring manufacturing and technological capability before energy-generating capacity. This is because the industrial strategy, with regard to solar PV, was focused on development of the export manufacturing industry and not on sustainable transition to a low-carbon society. This made the industry particularly prone to external impacts, for example the global recession and trade disputes. However, the presence of active and reflexive agents—both in private and public sector—and technological capability, already nurtured through exports, enabled the rapid transformation.

The existing transition framework has recently been challenged to accommodate issues such as the global dimension in a spatial sense (Coenen et al., 2012), the role of agents (Farla et al., 2012) and differentiated access and stock of capabilities in many forms (technological, absorptive and various types of institution) (Gallagher, 2006; Sauter and Watson, 2008). These challenges can be more acutely observed in developing and emerging country settings (Rock et al., 2009; Berkhout et al., 2009, among others). Moreover, developing countries are diverse and development pathways of different renewable energy are distinctive even within one country, as can be seen from the case study discussed in this paper, as well as in previous ones (Lema and Lema, 2012; Waltz and Delgado, 2012; Lewis, 2007). The framework by which to study the transition therefore needs to be made more flexible to accommodate diversity. For this purpose, further comparative studies in developing countries are needed to adjust the framework for formulating effective policy interventions.

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